The LAPS Method for Initializing Mesoscale Forecast Models with Clouds and Precipitation Processes

*Paul Schultz, John McGinley, Dan Birkenheuer, and Brent Shaw**

NOAA Research - Forecast Systems Laboratory
Boulder, Colorado

**[In collaboration with the Cooperative Institute for Research in the Atmosphere (CIRA), Colorado State University, Ft. Collins, Colorado]*

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ABSTRACT

The typical method for initializing limited-area models is by simply interpolating from a larger-scale model such as the National Centers for Environmental Prediction (NCEP) Rapid Update Cycle (RUC), Eta, or Global Forecast System (GFS), and perhaps refining the gridded fields with surface and rawinsonde data. "Local" models that use such larger-scale models for initialization (and lateral boundaries) begin their forecasts with clear sky, because there are significant obstacles in using cloud and vertical motion information from larger-scale models, and in assimilating data from satellites and radars into the local model. It can take as much as three hours of forecast time before the local model can construct reasonable fields of vertical motions, clouds, and precipitation. This paper presents a technique that addresses the spinup problem in mesoscale numerical predictions of cloud systems.

The Local Analysis and Prediction System (LAPS) "hot start" method for diabatic initialization of mesoscale models was first implemented Mesoscale Model version 5 (MM5), and is applicable to similar models such as the Regional Atmospheric Modeling System (RAMS), the Advanced Regional Prediction System (ARPS), the Navy's Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS), and the new Weather Research and Forecasting (WRF) model. The technique is based on three-dimensional analysis of cloud attributes such as coverage and type, and proceeds with methods of estimating the mixing ratios of cloud matter, precipitating water, and cloud vertical motions (i.e., saturated updrafts). A variational adjustment procedure, including both dynamic balancing and a strong continuity constraint, results in small adjustments to

the horizontal wind fields and the mass field that produce divergence patterns consistent with the diagnosed updrafts. As a result, a mesoscale model so initialized has realistic precipitation rates in the first time steps, maintains precipitating cloud structures, and provides useful precipitation forecasts in the critical 0-3 hour range.

The LAPS hot start has been running in real time since November 2000. Model forecast validation activities have coincided with various experiments conducted since then. In the first of these, results from over 40 model runs from the winter of 2000-2001 are compared with two kinds of parallel model runs. The first parallel run was initialized using the traditional method described above, and the second used a 3-h nudged assimilation of prior analyses. For these cases, the hot-start technique makes distinctly better forecasts for the first 3 h of the forecast, and retains its advantage out to 6 h. The second verification was done in conjunction with the International H_2O Project, in which the objective was forecasting mostly convective precipitation. The results of this experiment suggest a quantitative precipitation forecast (QPF) skill advantage over the NCEP Eta model and FSL's experimental version of the RUC model, in the first 6 h of model integration, especially in the 0-3 h period. The third and most recent validation exercise was for a Federal Highways Administration (FHWA) project that produced winter weather forecasts in support of highway snow removal operations, in which a 6-member ensemble of mesoscale models with LAPS hot-start diabatic initialization was used to inform a decision support software system. This experiment demonstrates the implementation of hot-start initialization in each of three different mesoscale models.

1. Introduction

Long-awaited advances in affordable computer performance now enable more realistic and more detailed representation of clouds and precipitation processes in real-time numerical weather prediction (NWP) models. For example, explicit microphysics methods previously used only in research models are now used in real-time applications at many universities, private companies, and laboratories. However, the benefits of these advances have been mostly in forecasts of 6 h and beyond. There has been less success in the first few hours of the forecasts. Even today, most mesoscale model users initialize forecasts with zero cloudiness, and accept the 2-3 h "spin up" between initial time and the first reasonable cloud distributions and precipitation rates.

Two factors make it difficult to initialize models with active, realistic clouds and precipitation processes. The first problem is detecting the clouds at the moment of forecast initialization. This requires high bandwidth real-time access to radar and satellite data, both of which require substantial processing to make estimates of condensate amounts in three dimensions, as required by numerical models. The second problem is less obvious. Simply inserting nonzero mixing ratios into mesoscale models such as the Pennsylvania State University / National Center for Atmospheric Research Mesoscale Model version 5 (MM5; Grell et al. 1995) will cause evaporation, cooling and incorrect downdrafts, unless such grid points have 100% relative humidity. Even so, numerical advection and diffusion will mix condensate with unsaturated air, still causing the unwanted downdrafts. Also, for initial clouds to survive and evolve, realistic vertical motions must be specified and properly balanced with respect to continuity and moist-thermodynamic constraints. This is diabatic initialization (DI).

This paper describes how the Local Analysis and Prediction System (LAPS), developed at the NOAA Forecast Systems Laboratory (FSL), addresses these problems.

LAPS was originally conceived to provide a means of combining various meteorological observations and measurements into a coherent analysis of the atmosphere at high temporal and spatial resolution, for use in weather forecasting (McGinley et al. 1991). In practice, forecasting operations require quick turnaround on small computers, so computational efficiency has always been a design criterion of LAPS. The need for nowcast products is evident, but useful forecasts beyond 1-2 h requires the application of one or more numerical models.

Snook et al. (1995) first applied LAPS to the problem of initializing mesoscale models. Although FSL has been running various configurations of the Colorado State University Regional Atmospheric Modeling System (RAMS; Pielke et al. 1992), MM5, and the National Centers for Environmental Prediction (NCEP) Eta model ever since, the spinup problem described above has been an obstacle to fully exploiting local datasets for better short-range precipitation predictions.

Ultimately, the solution to that problem will require providing the model with balanced cloud circulations, characterized by saturated moist-adiabatic ascent and dry adiabatic compensating subsidence, along with a realistic initialization of cloud and precipitation fields in three dimensions. Our approach is intended for grid meshes that resolve the saturated updrafts and compensating subsidence, as in Sun and Crook (1997), although applications to date have been on relatively coarse grids ($\Delta x \approx 4 - 10$ km).

Scale analysis of the thermodynamic energy equation appropriate for convective motions

$$w \frac{\partial \theta}{\partial z} \approx \frac{L}{c_p} \frac{\theta}{T} \frac{dq_c}{dt} \qquad (1)$$

shows that vertical velocity is strongly dominated by latent heat release:
Thus, our method simply ensures that cloudy grid points have upward momentum, and that horizontal wind divergence patterns precisely support those vertical motions.

Most prior efforts to mitigate spinup-related problems in short-range precipitation forecasting have used methods appropriate for modeling on grids too coarse to resolve saturated updrafts, and thus require parameterization of convective overturning. Tarbell et al. (1981) used observed surface rain rates to estimate three-dimensional latent heating rates, and solved a diabatic mesoscale version of the omega equation to determine a three-dimensional wind field balanced appropriately for a very large thunderstorm complex in the central U.S. The kinematics thus derived were suitable for driving the convective parameterization in the first time steps, which produced useful surface rain rates early in the model integration. Wang and Warner (1988) used a preforecast assimilation period to "nudge" the model solution to a three-dimensional heating rate field to achieve better vapor and condensate fields at startup time, allowing the model to develop the vertical motions and divergence during the assimilation period. Donner (1988) took the approach of modifying divergence, temperature and humidity fields so as to specifically trigger the convective parameterization to produce observed surface rain rates. Kasahara et al. (1992) demonstrate the success of this method in short-range forecasts of tropical precipitation systems. A similar approach is now in use by the NCEP Global Forecast System (Kanamitsu et al. 1991).

Another approach for improving spinup problems is the use of four-dimensional data assimilation (4DDA); i.e., cycling of short-range forecasts and analysis. The NCEP Rapid Update Cycle (RUC) model (Kim and Benjamin 2000). RUC uses prior forecasts to make first guesses of cloud, kinematic, and thermodynamic fields, which are then refined by using satellite data to determine areas that have more/less clouds than observed and then dry or moisten those areas appropriately, although wind and temperature fields are unaffected by this procedure. Still, precipitation forecast performance in the early hours of the forecast is improved by this practice. Raymond et al. (1995) also use satellite data to correct a model first guess in a 4DDA configuration, but takes the additional step of making thermodynamic adjustments to the initialization based on inferred three-dimensional latent heating fields. The necessary vertical motions and divergence are developed indirectly in the 4DDA cycling. Janisková et al. (2002) describe the development of a four-dimensional variational (4DVAR) approach in which the adjoint and tangent-linear versions of the cloud and longwave radiation parameterizations are applied to satellite radiance data to moisten cloudy air in the

European Centre for Medium-Range Weather Forecasting (ECMWF) model. Positive results in precipitation forecasts are reported but only for non-convective cloud types.

Unfortunately, these methods work in conjunction with cumulus parameterizations designed for use in models on relatively coarse grids ($\Delta x > 25$ km). Our present interest is in procedures suitable for cloud-system-resolving grid meshes that do not use convective parameterizations.

The DI method of Sun and Crook (1997) operates on grids of several hundred meters. This is a four-dimensional variational (4DVAR) method using a cost function that includes Doppler velocity data from one or more radars and radar reflectivity. The water fields and kinematics are thus very tightly coupled. Sun and Crook (1998) demonstrated good success on a small airmass storm in Florida. This is a very promising but expensive technique, and it is implemented around a model developed specifically for this process (and its adjoint), which discourages broader application. Wang et al. (2001) use a 4DDA approach with the ARPS model to perform intermittent assimilation of high-resolution radar data over a 1-h preforecast period. Their method is also quite expensive and probably not yet practical for routine use, but it worked remarkably well on a test case of a major tornado outbreak. Successes such as these are strong motivation for continued development of DI techniques for cloud-motion-resolving models. Each has been applied in test cases where excellent radar coverage was available, and both appear to be dependent on such coverage. The LAPS hot-start method is intended for the more typical situation that includes areas of spotty radar coverage, the holes in which can be accounted for (albeit approximately) by other datasets and extrapolation techniques (Albers et al. 1996).

Section 2 covers the LAPS methods of analyzing and estimating cloud and explains the variational techniques for balancing diagnosed clouds and vertical motions with the ambient wind, temperature, and humidity fields that provide smooth model startup. Section 3 deals with the practical aspects of loading mesoscale models with LAPS initialization grids. Section 4 describes early results and presents verification of forecast performance compared to other methods of model initialization and other forecast models. Section 5 is a summary and conclusions.

2. Analysis of water in all phases and variational adjustment to cloud motions

Proper initialization of precipitating cloud systems requires simultaneous consideration of the three wind components, temperature, pressure, water vapor, and several kinds of condensate. For example, in saturated updrafts, the local temperature and pressure together specify the (saturation) vapor amount. In cloud-resolving models where the horizontal and vertical scales of motion are similar, the convective heating rate is firmly tied to the local vertical velocity via the (appropriately scaled) thermodynamic energy equation. The same applies to downdrafts caused by evaporative cooling of rain, snow, etc. Of course, vertical motions are coupled to the horizontal wind field via the mass continuity equation. Failure to satisfy these relationships creates an interesting variety of nonphysical model errors.

Among the many difficulties encountered in this task, perhaps foremost is that the current observation system makes only indirect measurements of the particular physical attributes required by the models' equation sets. For example, the models' equations for water substance continuity use mixing ratios, and their initialization requires full three-dimensional specification of the mixing ratios of cloud liquid/ice, rain, snow, and perhaps one or more classes of precipitating ice. However, radars measure electromagnetic reflectivity, so assumptions about the hydrometeor type and amount are required. That, in turn, is affected by the temperature of the hydrometeors, but temperature measurements are not provided by radars and must be otherwise obtained. Likewise, satellites measure the radiative properties of clouds, air, and surface; however, these properties are related only indirectly to the temperature, humidity, and cloud species that the models actually need.

The LAPS method for initializing clouds, their associated kinematics, and precipitation proceeds in four steps.

First, univariate analyses of the wind, mass, humidity, and cloud variables are generated according to McGinley et al. (1991), Albers (1995), Albers et al. (1996) and Birkenheuer (1999)[1]. The temperature analysis depends heavily on the background model first guess and ACARS measurements, except at the surface where direct observations from meteorological aviation reports (METARs) and mesonets are combined with infrared

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[1] This is the part of LAPS that is implemented in the AWIPS workstations at all NWS warning and forecast offices.

satellite radiance. The wind analysis refines the background with data from Aircraft Communications and Reporting System (ACARS), profilers, Doppler radar velocities, and surface reports. The three-dimensional analysis of cloud type and cloud fraction uses the temperature analysis along with satellites, radars, cloud reports from METARs and voice pilot reports of cloud layers. The cloud analysis also produces gridded estimates of cloud liquid, cloud ice, and precipitating species such as rain and snow. Updates to the Albers et al. (1996) methods in the cloud analysis are reported by Birkenheuer et al. (2001). The humidity analysis incorporates the cloud analysis, multiple satellite radiance channels, surface observations, and more recently, GPS measurements of slant-path-integrated water vapor (see appendix).

The second step produces an estimate of the vertical motions within the analyzed clouds. The following rules are used:

- Cumuliform clouds are fitted with a parabolic vertical velocity profile whose magnitude is linearly dependent on cloud depth (Fig. 1). The magnitude of the parabola is not determined by the results of field studies (e.g., Cotton and Anthes 1989, p. 468), which would suggest values as large as 30 m s^{-1}. Instead, practical experience from modeling on 10-km grids indicates that a much smaller value leads to more realistic results. The maximum vertical velocity given by this algorithm is a linear function of grid increment; for example, the vertical velocities in Figure 1 correspond to a grid increment of 10 km.

- Stratiform clouds are assigned a small vertical motion (5 cm s^{-1}) held constant through the depth of the cloud. Heymsfield (1975) and Heymsfield (1977) indicate that vertical velocities in cirrus clouds are typically larger than this, sometimes greater than 1 m s^{-1}, but we have not yet seen great sensitivity to this. We should note that we have not yet tested this initialization method in cases with widespread marine stratocumulus, in which it should fail because the vertical circulations that support these clouds is not resolved by the models for which the method is intended.

- Cloud vertical motion is not assigned in the presence of precipitation, since air parcels containing precipitation are most often in downdrafts.

The third step is a dynamics adjustment procedure (McGinley 1987; McGinley and Smart 2001), in which the three-dimensional fields of mass and momentum are adjusted to force consistency with fundamental equations for momentum conservation, dry thermodynamics, and continuity. Using integral constraints in the form of Sasaki (1970), recast in discrete form, the solution fields are forced to satisfy dynamic constra (2) in a specified tolerance, and to satisfy mass continuity exactly. The penalty function *J* for the state variables *u, v, ω,* and Φ is cast in discrete grid form:

$$
\begin{aligned}
J = \sum_k \sum_j \sum_i & O_V(\hat{u}-u')^2 + O_V(\hat{v}-v')^2 + O_\omega(\hat{\omega}-\omega_c')^2 + O_\Phi(\hat{\Phi}-\Phi')^2 \\
& + \mu(\hat{u}_t)^2 + \mu\ (\hat{v}_t)^2 + \lambda\ (\hat{u}_x + \hat{v}_y + \hat{\omega}_p) \\
& + B_V\hat{u}^2 + B_V\hat{v}^2 + B_\Phi\hat{\Phi}^2 + B_\omega\hat{\omega}^2
\end{aligned}
$$

The variables denoted with a superscript carat (∧) are the solution differences from a background gridded first guess; the primed (') variables are the differences between the background and the univariate analyses described above. For the examples in this paper, the RUC model provided by NCEP is the source for background first-guess grids. Subscripts x and y refer to horizontal derivatives, and subscript p indicates a vertical derivative. The term ω_c is the cloud vertical motion estimates. Weights on the observations (**O**) and the background (**B**) are defined from known error characteristics and estimates of fit from the first step described above and the background model, respectively. The weighting factor μ adjusts the magnitude of the residual Eulerian time tendencies of u and v relative to the other constraints and provides a balance among the mass and momentum fields. The Lagrange multiplier λ ensures that continuity is satisfied to the limits of computational accuracy. The Eulerian time tendencies u_t and v_t are given by:

$$\hat{u}_t = -(u_b\hat{u}_x + \hat{u}u_{bx} + v_b\hat{u}_y + \hat{v}u_{by} + \omega_b\hat{u}_p + \hat{\omega}\, u_{bp}) - \hat{\Phi}_x + f\,\hat{v} - D(\hat{u})$$

$$\hat{v}_t = -(u_b\hat{v}_x + \hat{u}v_{bx} + v_b\hat{v}_y + \hat{v}v_{by} + \omega_b\hat{v}_p + \hat{\omega}\, v_{bp}) - \hat{\Phi}_y - f\,\hat{u} - D(\hat{v}) \qquad (3)$$

The background fields $(\ )_b$ are utilized so the nonlinear terms become quasi-linearized with known estimates from the previous analysis step.

Closeness of fit of the analyzed vertical velocity $\hat{\omega}$ to the cloud-based estimate ω_c depends on the weight O_ω, which is selected based on expected errors in the estimates of ω_c. Depending on the grid point values of O_V (inverse variances of estimated analysis error from step 1 above) and the quality of the background B_V (inverse variances from local model error characteristics), the input cloud vertical motions will be closely fit or altered. Figure 2 shows two simulated cases with large and small O_ω. Note that the core updraft speed and horizontal scale vary. The adjustment is primarily to the divergent part of the wind, however the nonlinear terms in the constraint equations do produce slight adjustments to the rotational component, and hence geopotential and temperature. This can sometimes warm the cloud column so that some cloudy grid points become subsaturated. Thus, the fourth step is to reset the relative humidity to 100% at such grid points. Failure to do so causes instantaneous evaporation, along with the associated cooling and subsequent false downdrafts, in the first few time steps (Fig. 3). Other aspects of this part of the procedure are discussed in the next section.

By minimizing the time tendencies u_t and v_t we ensure that the analyzed (initial) fields have mass fields consistent with slowly evolving horizontal motions, thus ensuring that vertical motions also evolve slowly. This is the crucial step that results in good temporal continuity between the analyzed cloud fields and the forecasts thereof in the first few model time steps. Furthermore, the balancing procedure minimizes the time tendencies of the mass and wind fields at the lateral boundaries and thus provides a smooth start largely devoid of nonphysical gravity waves which characterize model runs initialized without some sort of equivalent procedure (Fig. 4).

The method has been tested mostly using MM5, but is equally applicable in any model with explicit representation of cloud and precipitation processes.

3. Model initialization

The LAPS diabatic initialization technique, or "hot start," has been used to initialize various real-time mesoscale NWP models at FSL since the summer of 2000. These real-time runs have been used as quasi-operational systems for the purpose of testing and improving the hot start technique, providing prototype products to operational meteorologists, supporting field experiments, and obtaining subjective and objective verification.

The first model utilized with the LAPS hot start was MM5 using the Schultz (1995) microphysics option. Whereas the goal of the LAPS analysis component is to produce a very accurate analysis of the real atmosphere, this may not be ideal for initializing an NWP model (Schultz and Albers 2001), so an additional step in the processing adjusts the hydrometeor and humidity fields to resemble values typically seen in the output of nonhydrostatic numerical models at a given horizontal resolution. The steps involved in creating model realistic fields are:

- Hydrometeor concentrations are scaled using a grid-scale dependent factor: $q_m = q_L(2000 / \Delta x)$ where q_m is the model-realistic mixing ratio of the hydrometeor species, q_L is the LAPS-analyzed value, and Δx is the model grid spacing in m. One-hour model precipitation forecasts show very little sensitivity to small changes in input hydrometeor concentrations.

- After the grid-dependent scaling, the cloud liquid and cloud ice concentrations are limited to not exceed model-specified autoconversion thresholds for rain ($0.5\ g\ kg^{-1}$) and snow ($0.1\ g\ kg^{-1}$), respectively. This prevents unrealistically rapid collection, fallout, and downdrafts in the early time steps.

- Any grid box volume containing cloud liquid and/or ice is raised to saturation with respect to liquid and/or ice if it is not already saturated, and if the analyzed cloud cover for the grid point is greater than a threshold that varies with grid increment (e.g., 60% for Δx = 10 km). This prevents instantaneous evaporation of the cloud water in the first model time step, and very rapid sublimation of cloud ice in the first few time steps, thereby providing an initial cloud field that evolves realistically.

Although FSL has been running MM5 using hot start DI since 2000, the pragmatic modifications described above have only recently been added as experience was gained during the past three years. Nevertheless, the forecasts produced from these model runs have demonstrated useful skill in forecasting clouds and precipitation in the early hours of the forecasts, the period models are typically going through the “spinup” process. Figure 5 shows an example of a cloud forecast at 20-min intervals for the first hour of a simulation using the MM5 model. Although the model quickly readjusts the distribution of cloud liquid and ice within the microphysics scheme, there is overall very good continuity of the cloud field, as verified with satellite and radar imagery (not shown).

By design, the hot-start initialization method, like the rest of the LAPS system, is model-independent; i.e., it should work with any full-physics model, although it may require adjustments to thresholds related to the model's autoconversion parameterizations. To date, in addition to MM5, the LAPS hot start has been implemented in RAMS and the new Weather Research and Forecast model (WRF; Michalakes et al. 2001).

4. Verification

Since January 2001, forecasts from diabatically initialized MM5 runs have been provided routinely four times daily to forecasters at the NWS Forecast Office in Boulder, CO, which is collocated with FSL, on their Advanced Weather Interactive Processing System (AWIPS). Since that time, FSL has received valuable subjective feedback from the forecasters. Details are provided in Shaw et al. (2001b); some of the highlights:

- The model does a good job of predicting localized precipitation patterns related to subtle topographic features (e.g., the Cheyenne Ridge and Palmer Divide) that are not well represented in the national models.

- The forecasts provide excellent guidance in determining the depth of low-level clouds in the mountain valleys and along the Front Range during upslope situations, as well as the dissipation of such clouds.

- The MM5 forecasts are much better at forecasting local wind variations than the national models, particularly those variations due to subtle orographic effects (Poulos et al. 1999). Examples of the model's ability to correctly diagnose and forecast the presence of the "Longmont Anticyclone" and the "Denver Cyclone" are discussed in Szoke and Shaw (2001).

- The surface temperature forecasts do a much better job of representing significant gradients due to minor terrain differences, including drainage flows, and deeper layers of cold air that do not readily modify due to mixing.

- Mountain wave activity is handled very well by the MM5 forecasts. In these situations, the model does particularly well in defining the extent of the downward mixed westerly winds and the convergence zone between these winds and weak easterly winds.

These examples are typical improvements gained with the use of a mesoscale NWP model in areas of highly variable terrain, and are not necessarily related to the method of initialization, but they illustrate two important points: (1) local operational meteorologists have confidence in the diabatically initialized forecasts based on their continued willingness to use the guidance, and (2) the DI does not appear to be degrading the model's treatment of forecast parameters not related to precipitation.

Of course, the primary motivation for developing DI is to improve very short-range precipitation forecasts. Three objective verification exercises have been conducted in conjunction with forecasting experiments to assess the impact of hot-start DI on numerical precipitation forecasts. Figure 6 shows the model domains for each of these experiments, which will be discussed next.

a. Winter 2000-2001 Rocky Mountain region forecasts

The first verification experiment compares solutions from three different initialization methods during the 2000-2001 winter season in the Rocky Mountain region. The models were initialized four times daily, at 0000 UTC and every 6 h thereafter. Each forecast produced hourly forecast grids out to 24 h. All three runs used exactly the same model configuration and lateral boundary conditions from the operational NCEP Eta model on the 40-km CONUS grid distributed the NWS field offices. The only difference between the three runs was the initialization method. The model run initialized with the LAPS hot start is referred to as MM5HOT. The MM5WARM runs used a 3-h 4DDA as an attempt to reduce the spinup time for cloud and precipitation processes. State variables from the hourly LAPS analyses valid for the 3-h period ending at the initialization time were used for the nudging period. While this technique does reduce spinup time, it has the disadvantage of requiring additional computational time.

The MM5COLD run used no LAPS analysis, but rather was simply initialized using the state variables from the 6-h Eta forecast from the same Eta cycle used for the lateral boundary conditions. This is a typical initialization method used by many real-time mesoscale model users, and relies upon the higher-resolution terrain and nonhydrostatic dynamics to improve upon the larger-scale forecast provided by the regional or national model grids.

For each cycle, each of the three forecast runs were verified against LAPS analysis grids for the domain. The same LAPS analysis was used to verify all three configurations. Furthermore, these LAPS analyses were fully independent, as they used the operational RUC model as their first guess. For each of the first 12 forecast hours, traditional skill scores were computed for various parameters, including clouds and precipitation. The skill scores were computed by comparing the analysis and forecast grids on a gridpoint-by-gridpoint basis (i.e., neighboring points are not considered). Thus, slight timing or spatial errors can significantly impact the skill scores. Figure 7 shows the equitable skill score (ESS) for hourly snowfall forecasts and cloud cover from the verification period. ESS (Gandin et al. 1992) is computed using:

$$ESS = (C - E)/(F + O - C - E), \qquad (4)$$

where C is the number of points where threshold was forecast and observed, F is the number of points where forecast exceeded threshold, O is the number of points observed to exceed threshold, T is the total number of points in the horizontal domain, and an approximate number of forecasts correct due strictly to chance is estimated by $E = F * O / T$.

These graphs visually demonstrate the improvement in the short-range forecast of clouds and precipitation due to the DI technique. Additionally, both the MM5HOT and the MM5WARM values demonstrate that skill is improved during the early hours when additional data are assimilated using an analysis system rather than using a simple "nestdown" from a regional model (in this case, the operational Eta). Furthermore, the model spinup time for this particular domain can be inferred from the graphs by noting the length of the period between the initial time and the time that MM5ETA skill is statistically comparable to the MM5HOT and MM5WARM cases. For this domain, this time frame appears to be on the order of 6 h. The postprocessor used with the LAPS modeling system provides the forecast grids incrementally to the forecasters as they are produced, so the 1-h forecast is typically available at or before its valid time. Thus, the additional skill provided by the diabatic initialization would be beneficial, particularly for automated forecast systems that use NWP grids as their input.

The convergence of model skill in the later hours demonstrates the dominance of the lateral boundary conditions on the resulting forecast for the limited domain. We speculate, however, that the use of a land surface model component in the forecast model combined with a rapid data assimilation cycle may lengthen the time period of added value for the diabatically initialized forecasts due to the earlier spinup of precipitation processes (and thereby changes to the soil moisture field).

2) Verification of IHOP Model Runs

The LAPS hot start DI method was used to initialize real-time MM5 runs during the International H_2O Project (IHOP) field experiment (Weckworth et al. 2003) which was conducted over the "tornado alley" area of midwestern US (Fig. 6) in May and June 2002. This project provided an excellent opportunity to test the technique in a summer convective regime. It should be noted that the 12-km grid increment used for these model runs is probably a factor of at least three too large for treating deep convection with only explicit microphysics, and there certainly were errors of the type described in Weisman et al. (1997) seen routinely during IHOP.

During the entire experiment, precipitation forecasts from the hot-started MM5 runs were verified against pointwise rainfall observations (as opposed to the gridded predictands used in the previous test). In addition to the MM5 forecasts, other operational and research models from NCEP, FSL, and NCAR were also verified, allowing a direct comparison to other models and initialization techniques.

Since this was the first quantitative assessment in strongly convective cases it was not surprising that significant errors (which did not cause serious problems in the winter cases discussed above) were evident in the early going. In particular, a large positive bias in the early hours of the forecasts was identified early in the experiment; additionally, the model had significant problems with elevated convective systems, which are frequently observed in the central U.S. in the overnight and early morning hours. This led to several refinements which were implemented on 24 May. First, the magnitudes of initialized hydrometeor concentrations were made dependent upon horizontal resolution after examining the LAPS hydrometeor analysis methods, which produce values that are more representative of peak amounts than grid-box averages. Second, the depth below cloud base where the inserted vertical velocity becomes nonzero was reduced from 25% of the cloud depth to 10%. Note that the comparisons presented here were computed over model runs that came after the initialization modifications implemented on 24 May.

Figure 8 shows the equitable skill score and frequency bias for the 3-h QPF from the 12-km MM5 domain and the operational 12-km Eta from NCEP. The diabatically initialized MM5 forecasts show a significant improvement in forecast skill across all the precipitation thresholds, and in particular for the higher threshold. For 3-h precipitation amounts greater than or equal to 0.75 in, the MM5 forecasts continued to show positive skill whereas the operational Eta had no skill, despite being run at the same horizontal spatial resolution and its coupling with the 3DVAR-based Eta Data Assimilation System.

Subsequent to the experiment's conclusion, several additional enhancements were made that improved the IHOP forecasts. Plans for rerunning the entire IHOP experiment with the new improvements are in place, and the results will be discussed in a future publication.

c) Winter 2003 Verification

As part of a project sponsored by the Federal Highways Administration (Mahoney 2001), FSL ran an ensemble of mesoscale models during the winter of 2003 (Schultz 2002) over an area centered on Iowa (Fig. 6, panel 3). This is known as the Maintenance Decision Support System (MDSS) project. The MM5, WRF, and RAMS models were run 4 times per day out to 27 h (to provide 24-h forecast service after about 2 h to run the models). As in the IHOP field experiment, QPFs from these forecasts were verified against rain gauge observations (Fig. 9); these are 3-h forecasts of 3-h precipitation amounts. Our intent with this discussion is to demonstrate progress toward high-resolution, diabatically initialized ensemble numerical weather prediction.

The MM5 and WRF modeling systems provided forecasts of very similar Equitable Skill Scores across the range of precipitation amounts. The frequency bias of the MM5 forecasts is very close to 1.0, or optimum, but the WRF model forecasts show a consistent positive bias. There are several microphysics options provided with the WRF model, and private communications with collaborators in the WRF development community encourage us to test these options to resolve this problem.

The RAMS model forecasts show very large biases in forecast precipitation amount and area (which also depressed skill scores) because of a known problem in the model's microphysics configuration. Other microphysics options are available, so there is reason to believe that performance similar to the other two modeling systems is attainable.

5. Summary and discussion

This paper presents the motivation and formulation of the LAPS hot-start method for DI of mesoscale forecast models. The verification scores used for evidence of its success were computed over forecasts made by the MM5 model, although the method has been implemented for the RAMS and WRF models as well.

One key attribute of this DI method is its efficiency. In its current implementations, the hot-start initialization takes about as long to execute as about 30 min of forecast model integration. In a typical example on a modest Beowulf cluster, a model forecast initialized with 1500 UTC data will have all the satellite, radar, METAR, profiler and ACARS data by 1530 UTC, the analysis executes for about 10 minutes after that, the initialization executes for about 7 minutes after that, and the mode actually starts running at 1545. Thus the model's 1-h "forecast" is available only a few minutes before its valid time, but 2- and 3-h forecasts (of considerable skill) are available with plenty of lead time. In practice, this turnaround time is too large to be useful in explicit severe thunderstorm prediction, for example, but virtually any larger-scale longer-lived cloud/precipitation system, including organized convective complexes, frontal squall lines, winter cyclones, and hurricanes, can be skillfully predicted with useful lead times. This unprecedented level of real-time modeling service could potentially be used to make responses to floods and blizzards much more efficient and result in tangible savings in lives and property. It is currently being applied in various applications targeting winter weather, fire weather, and coastal waters forecasting, all in real time, all unattended, and all very reliable.

The major forecast centers of the U.S. and Europe have announced plans to achieve cloud scale DI sometime in the next several years, and they all plan to use some sort of 3DVAR or 4DVAR approach. They do not do so now because those methods have not been developed (beyond simple demonstrations of concept) and take very large resources to execute. It is likely that some aspects of this work will be useful in the development of DI for the models used at the national centers, but that is not the primary application for which this method is intended. The potential value in this technology is in the short-range prediction of precipitation and related phenomena, which in the U.S. is primarily the responsibility of the 100+ NWS Warning and Forecast Offices across the country. This application requires great efficiency because large computing systems cannot be made available to all the forecast offices, yet fast turnaround time is required for supporting short-term predictions. Decisions to uniformly implement this or any new technology in NWS forecast offices are made on the basis of expectations of improved forecast services, which we have begun to demonstrate herein.

Acknowledgments. Most of the verification skill scores reported here were computed using the Real-Time Verification System developed at FSL. The authors would like to express their appreciation for the efforts of RTVS project manager Jennifer Mahoney and developers Judy Henderson, Mike Kay, Andrew Loughe, and Beth Sigren. Also, we thank Stan Benjamin for his review of the original manuscript, which led to several

improvements in the final version.

APPENDIX A

The LAPS humidity package

In 2001 the LAPS moisture package was updated to a variational minimization scheme to simultaneously derive a solution that best fit all moisture data and background data input to LAPS. This system was designed to be robust such that if data sources were not available, the system would still function. The solution is found by minimizing the functional

$$
\begin{aligned}
J = {} & S_{SAT} \sum_{k=1}^{7} \frac{GT(g_i)[R(t,cq,o_3)_i - R_i^o]^2}{E_{SAT}^2 L_{SAT}} + \sum_{i=1}^{N} \frac{(1-c_i)^2}{E_{BACK}^2} \\
& + S_{GPS} \frac{(\sum_{i=1}^{N} c_i q_i - Q^{GPS})^2}{E_{GPS}^2 L_{GPS}} \\
& + S_{GVAP} \sum_{j=1}^{3} \frac{G(g)(\sum_{i=1}^{N} P_{ji}(c_i q_i) - Q_j^{GVAP})^2}{E_{GVAP_j}^2 L_{GVAP}} + S_{CLD} \sum_{i=1}^{N} \frac{g_i [c_i q_i - q_s(t_i)]^2}{E_{CLD}^2 L_{CLD}} .
\end{aligned}
\tag{A.1}
$$

Each term in A.1 contributes to J, the penalty term such that the “best” solution minimizes J. A.1 contains several terms; each pertains to a data type or background field. Each term in (A.1) is modified by the variable S, which is a switch (with the exception of the background term, which is always on). Thereby, the terms can be used or left out, depending on whether or not data are available or if clouds are present. Furthermore, a user can expand the functional for new datasets by simply creating a new term.

The first term in A.1 is a forward radiative transfer model that produces a simulated radiance based on temperature, moisture, and ozone profiles along with the temperature of the surface or cloud top, optical depth, and the pressure of that radiating surface (i.e., surface pressure or cloud top pressure whichever applies). The forward model used for this work was obtained from NESDIS, but any such model could be used in this system. The second term is the background minimization, the closer c is to unity, the closer the solution is to the background. The third term is the GPS integrated precipitable water term. The fourth is used if GOES-derived product layer water vapor is available. The last term adjusts for cloud saturation. All terms that are affected by cloud (i.e., IR sensor dependant data) are affected by the g variable that can be used in partly cloudy situations.

Variables used in A.1:

C_i Coefficient vector applied to q to adjust the moisture field. Ideally this would have the same dimensions as q has levels, but may be reduced depending on computer resources. Adjustment of this parameter is in essence the variational fit to the solution, i.e., $c_i q$ becomes the adjusted q field. The adjustment coefficient is a scalar with a lower limit of 0 (never negative). A value of 1 indicates no change to the background. Because of this, the system will only work with a quantity such as temperature or humidity that uses absolute units. For example, using this approach to analyze temperature in degrees F will fail.

q Specific humidity profile at one LAPS grid point.

R Forward-modeled radiance or radiance observation with the superscript o.

i Index for the LAPS vertical (vector dimension of q), with a current maximum of 40 to accommodate the climatological stratospheric layers needed for the forward radiance model.

k Index indicating the satellite sounder or imager channel used, currently 3 moisture and 4 thermal channels are used.

Q^{GPS} Total precipitable water measurement from GPS, a 2D preanalyzed field that has a corresponding spatial weighting influence field.

E Error function (squared quantity) that describes the observation or background error, subscripted by observation type.

L Spatial weighting term subscripted by observation type. This weights the smoothed (preanalyzed) field value by its proximity to the observation and reflects the horizontal influences of the measurement. Each data source may have an associated gridded field of spatial-weighting terms characterizing its proximity to the observation and its spatial representation, depending in part on the differences between the LAPS grid and the spatial resolution of the data source.

P Function to convert from pressure to sigma coordinates, GOES derived layer water values are defined in sigma coordinates.

Q^{GVAP} GOES vapor total precipitable water layer data. The layers are defined in sigma coordinates and vary grid point to grid point.

j Index of the GVAP layer, with a current maximum of 3 (1 is lowest, 3 is highest).

Cld Cloud function designating cloudy regions in the vertical, with dimensions of q.

J Functional to be minimized.

t Temperature profile (LAPS) at the same location as q.

S Logical switch for the observation type to be present or not. Each term in the functional can be easily included or excluded depending on the presence of the data source. Also new data sources can be added by including new terms.

$q_s(t)$ Saturated q as a function of temperature.

g Cloud fraction indicator as a function of level.

G Function of *g* such that it indicates cloud in the column. For radiance measurements, this has the advantage of disabling IR terms including GVAP. Finally, the GPS term would be unaffected by clouds in principle since the data source can deliver data in cloudy areas. However, the analysis needs to probably give more credence to the cloud field, since it is vital the cloud field complements the moisture field. *G* can be a linear function of cloud such that it might serve to help define partly cloudy regions by allowing a smooth gradient from total through partly cloudy to clear air.

GT Function similar to *G,* but it may be nonlinear and can match the satellite radiometer's field of view.

References

Albers, S.C., J.A. McGinley, D.L. Birkenheuer, and J.R. Smart, 1996: The Local Analysis and Prediction System (LAPS): Analyses of clouds, precipitation, and temperature. *Wea. Forecasting,* **11,** 273-287.

Albers, S.C., 1995: The LAPS wind analysis. *Wea. Forecasting,* **10,** 342-352.

Birkenheuer, D., 1999: The effect of using digital satellite imagery in the LAPS moisture analysis. *Wea. Forecasting,* **14,** 782-788.

Birkenheuer, D., B. Shaw, S. Albers, and E. Szoke, 2001: Evaluation of local-scale forecasts for severe weather of July 20, 2000. *14th Conf. On Numerical Weather Prediction,* Ft. Lauderdale, FL, Amer. Meteor. Soc., 81-84.

Black, T.L., 1994: The new NMC mesoscale Eta Model: Description and forecast examples. *Wea. Forecasting*, **9**, 265-278.

Cotton, W.R. and R.A. Anthes, 1989: *Storm and Cloud Dynamics.* Academic Press, 883 pp.

Donner, L.J., 1988: An initialization for cumulus convection in numerical weather prediction models. *Mon. Wea. Rev.,* **116,** 377-385.

Gandin, L. S. and A. H. Murphy, 1992: Equitable skill scores for categorical forecasts. *Mon. Wea. Rev.,* **120,** 361-370.

Grell, G.A., J. Dudhia, and D.R. Stauffer, 1995: A description of the fifth-generation Penn State NCAR Mesoscale Model (MM5). *NCAR Technical Note TN-398+STR,* 122 pp.

Heymsfield, A.J., 1975: Cirrus uncinus generating cells and the evolution of cirriform clouds. Part I: Aircraft observations of the growth of the ice phase. *J. Atmos. Sci.,* **32,** 799-808.

Heymsfield, A.J., 1977: Precipitation development in stratiform ice clouds: A microphysical and dynamical study. *J. Atmos. Sci.,* **34,** 367-381.

Janisková, M., J.-F. Mahfouf, and J.-J. Morcrette, 2002: Preliminary studies on the variational assimilation of cloud-radiation observations. *Quart. J. Roy. Meteor. Soc.,* **18,** 2713-2736.

Kanamitsu, M., and Coauthors, 1991: Recent changes implemented into the global spectral system at NMC. *Wea. Forecasting,* **6,** 425-435.

Kasahara, A., A.P. Mizzi, and L.J. Donner, 1992: Impact of cumulus initialization on the spinup of precipitation forecast in the tropics. *Mon. Wea. Rev.,* **120,** 1360-1380.

Kim, D., and S.G. Benjamin, 2000: An initial RUC cloud analysis assimilating GOES cloud-top data. *9th Conf. On Aviation, Range, and Aerospace Meteorology.* Orlando, FL, Amer. Meteor. Soc., 522-524.

Mahoney, J. L., J. K. Henderson, B. G. Brown, J. E. Hart, A. Loughe, C. Fischer, and B. Sigren, 2002: The Real-Time Verification System (RTVS) and its application to aviation weather forecasts. *10th Conference on Aviation, Range, and Aerospace Meteorology*, Portland, OR., Amer. Meteor. Soc., 323-326.

Mahoney, W., 2001: An advanced winter road maintenance decision support system. *11th Annual ITS America Meeting,* Miami, FL, Amer. Meteor. Soc.

Mathewson, M., T. LeFebvre, and T. Hansen, 2000: The Interactive Forecast Preparation System. *FSL Forum,* N. Fullerton, Ed., December 2000, NOAA Forecast Systems Laboratory, Boulder, CO (http://www.fsl.noaa.gov/~vondaust/f2000/).

McGinley, J.A., S. Albers, and P. Stamus, 1991: Validation of a composite convective index as defined by a real-time local analysis system. *Wea. Forecasting,* **6,** 337-356.

McGinley, J.A., 1987: A variational objective analysis system for analysis of the ALPEX data set, *Meteor. Atmos. Phys.,* **36,** 5-23.

McGinley, J. A., and J. R. Smart, 2001: On providing a cloud-balanced initial condition for diabatic initialization. *14th Conf. on Numerical Weather Prediction,* Fort Lauderdale, FL, Amer. Meteor. Soc., 40-44.

Michalakes, J., S. Chen, J. Dudhia, L. Hart, J. Klemp, J. Middlecoff, and W. Skamarock, 2001: "Development of a next generation regional weather research and forecast model. *Developments in Teracomputing: Proceedings of the Ninth ECMWF Workshop on the Use of High Performance Computing in Meteorology.* World Scientific, Singapore, 269-276.

Pielke, R. A., and Coauthors, 1992: A comprehensive meteorological modeling system -- RAMS. *Meteor. Atmos. Phys.,* **49,** 69-91.

Poulos, G.S., D.A. Wesley, J.S. Snook, and M.P. Meyers, 2002: A Rocky Mountain storm. Part I: The blizzard - Kinematic evolution and the potential for high-resolution numerical forecasting of snowfall. *Wea. Forecasting*, **17**, 955-970.

Raymond, W.H., W.S. Olson, and G. Callan, 1995: Diabatic forcing and initialization with assimilation of cloud water and rainwater in a forecast model. *Mon. Wea. Rev.,* **123,** 366-378.

Sasaki, Y., 1970: Some basic formalisms in numerical variational analysis. *Mon. Wea. Rev.,* **98,** 875-883.

Schultz, P., 1995: An explicit cloud physics parameterization for operational numerical weather prediction. *Mon. Wea. Rev.,* **123,** 3331-3343.

Schultz, P., 2002: Using ensembles of numerical weather forecasts for road weather prediction. *18th Conf. On Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology,* Orlando, FL, Amer. Meteor. Soc., 32-34.

Schultz, P., and S. Albers, 2001: The use of three-dimensional analyses of cloud attributes for diabatic initialization of mesoscale models. *14th Conf. on Numerical Weather Prediction,* Fort Lauderdale, FL, Amer. Meteor. Soc., J122-J124.

Shaw, B. L., J. A. McGinley, and P. Schultz, 2001a: Explicit initialization of clouds and precipitation in mesoscale forecast models. *14th Conf. on Numerical Weather Prediction*, Fort Lauderdale, FL, Amer. Meteor. Soc., J87-J91.

Shaw, B. L., E. Thaler, and E. Szoke 2001b: Operational evaluation of the LAPS-MM5 "hot start" local forecast model. *18th Conf. on Wea. Anal. and Fcst.,* Fort Lauderdale, FL, Amer. Meteor. Soc., 160-164.

Snook, J. S., J. M. Cram, and J. M. Schmidt, 1995: LAPS/RAMS: A nonhydrostatic modeling system configured for operational use. *Tellus,* **47A,** 864-875.

Sun, J., and A. Crook, 1997: Dynamical and microphysical retrieval from Doppler radar observations using a cloud model and its adjoint. Part 1: model development and simulated data experiments. *J. Atmos. Sci.,* **54,** 1642-1661.

Sun, J., and A. Crook, 1998: Dynamical and microphysical retrieval from Doppler radar observations using a cloud model and its adjoint. Part 2: retrieval experiments of an observed Florida convective storm. *J. Atmos. Sci.,* **55,** 835-852.

Szoke, E., and B. L. Shaw, 2001: An examination of the operational predictability of mesoscale terrain-induced features in eastern Colorado from several models. *9th Conf. on Mesoscale Processes,* Fort Lauderdale, FL, Amer. Meteor. Soc., 380-383.

Tarbell, T.C., T.T. Warner, and R.A. Anthes, 1981: An example of the initialization of the divergent wind component in a mesoscale numerical weather prediction model. *Mon. Wea. Rev.,* **109,** 77-95.

Wang, D., K.K. Droegemeier, D. Jahn, K.-M. Xu, M. Xue, and J. Zhang, 2001: NIDS-based intermittent diabatic assimilation and application to storm-scale numerical weather prediction. *14th Conf. on Numerical Weather Prediction*, Fort Lauderdale, Amer. Meteor. Soc., J125-J128.

Wang, W., and T.T. Warner, 1988: Use of four-dimensional data assimilation by Newtonian relaxation and latent-heat forcing to improve a mesoscale-model precipitation forecast: A case study. *Mon. Wea. Rev.,* **116,** 2593-2613.

Weckwerth, T.M., D.B. Parsons, S.E. Koch, J. Moore, M.A. LeMone, C. Flamant, B. Geerts, and J. Wang, 2003: An overview of the International H_2O project and some preliminary highlights. *Bull. Amer. Meteor. Soc.,* in review.

Weisman, M. L., W.C. Skamarock, and J. B. Klemp, 1997: The resolution dependence of explicitly modeled convective systems. *Mon. Wea. Rev.,* **125,** 527-548.

Xue, M., 2000: K. Droegemeier, V. Wong, 2000: The Advanced Regional Prediction System (ARPS) - A multi-scale non-hydrostatic atmospheric simulation and prediction model. Part 1: model dynamics and verification. *Meteor. Atmos. Phys.,* **75,** 161-193.

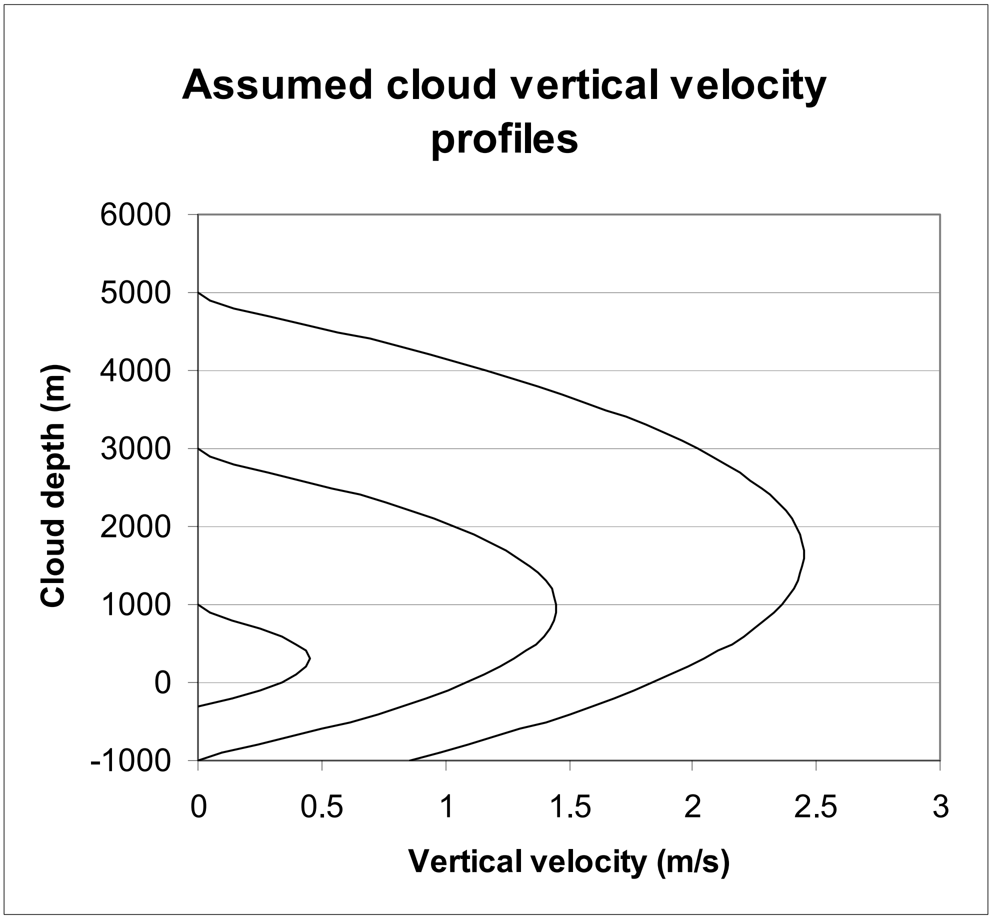


Fig. 1. Cloud vertical motion profiles for cumuliform clouds of three heights (1 km, 3 km, and 5 km). Note that the parabolic shape begins slightly below cloud base (i.e., 0 m).

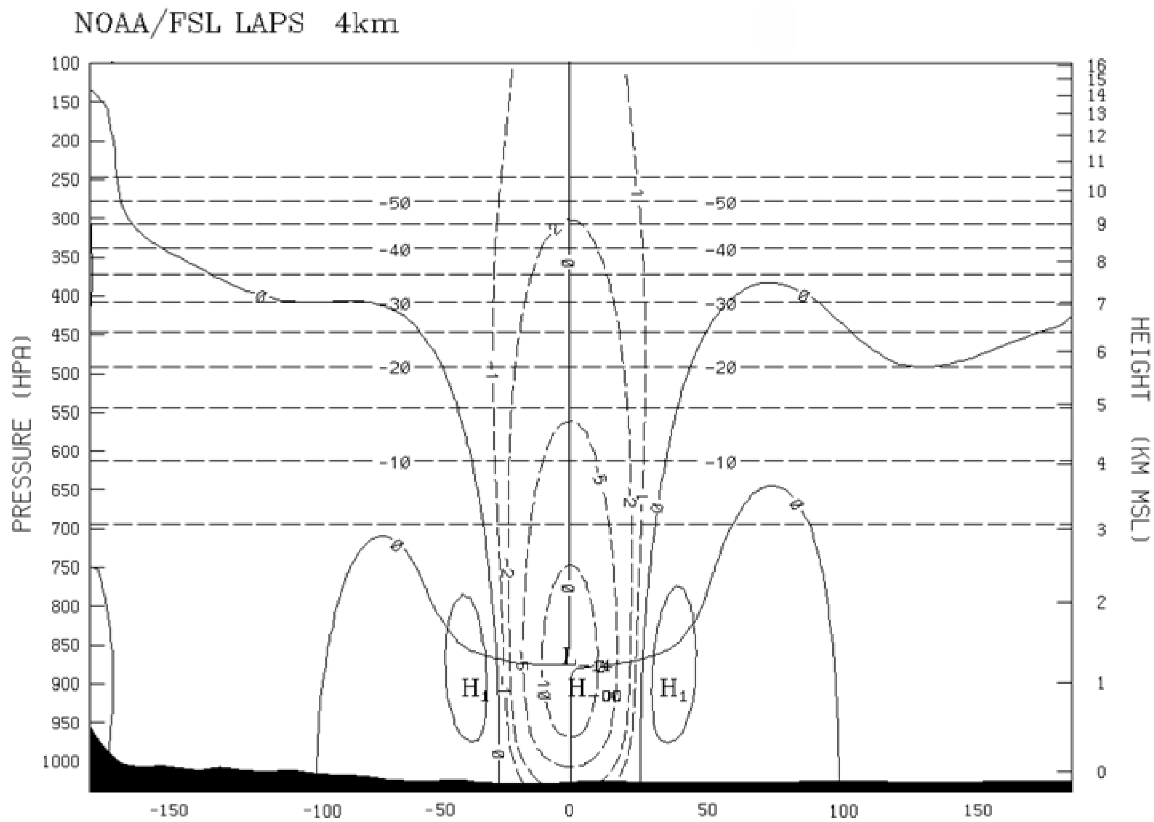


Fig. 2 continues next page.

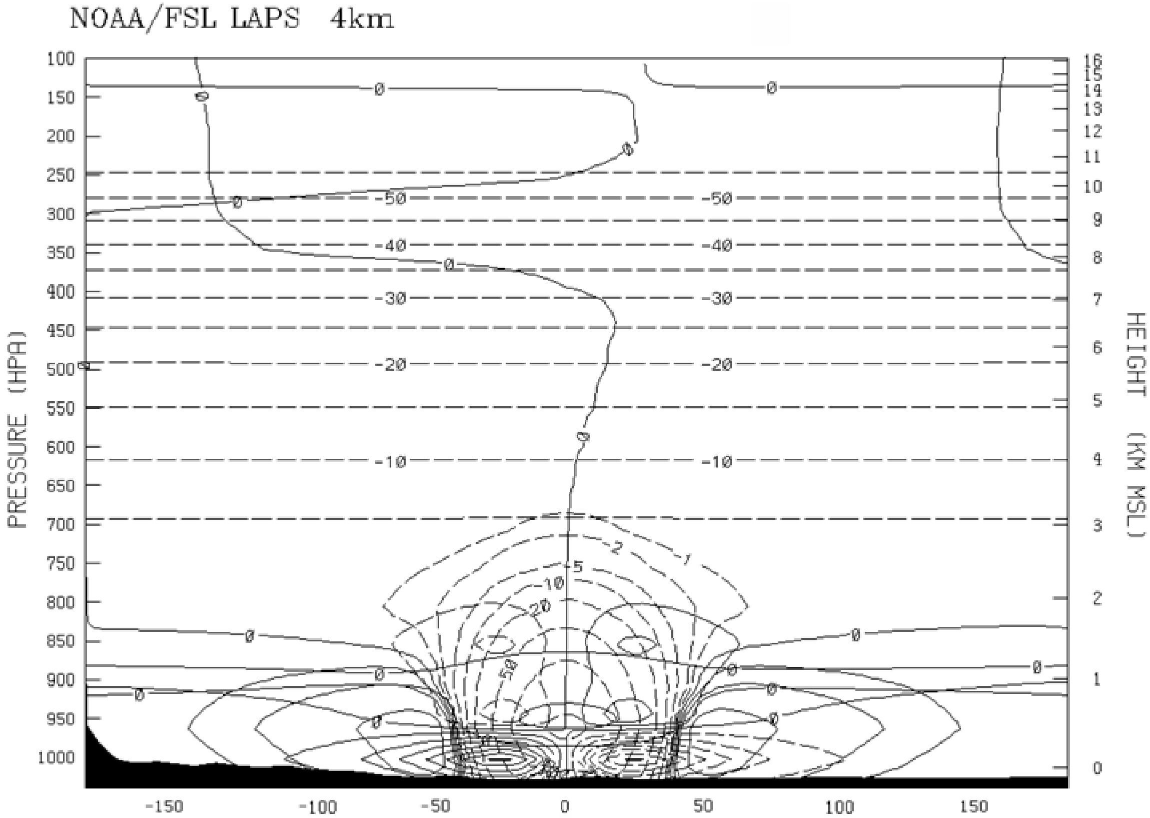


Fig. 2. Cross-section W-E centered on Washington DC. Hypothetical elliptical dry updraft with maximum of –60 μbar s^{-1} is inserted in center of grid at 950 MB. Contours show LAPS analyzed vertical motion (μbar s^{-1}), horizontal motion in plane (U-component, m s^{-1}), and temperature (C) in horizontal dashed lines. For the purposes of illustration, input horizontal motions are set to zero and the temperature profile is constant across the grid. The top figure shows the impact of a low weight on O_ω (0.1 sec^2 Pa^{-2}). Such a value is chosen when large errors are expected in the input vertical motions. Convergence in the horizontal wind component is weak but has been spread vertically, corresponding to the vertical extent of the updraft. The peak input value has been reduced and the impact on the temperature field is weak. The bottom figure shows the impact of a high weight on O_ω (100 sec^2 Pa^{-2}). Such a value is appropriate when input vertical motions have low error. The vertical motions are nearly reproduced as inserted. Convergence in the horizontal wind component is very strong below the peak updraft and divergence is stronger aloft, but the adjusted horizontal winds do not penetrate far vertically, since the vertical extent of the updraft is small. Impact on the temperature field is strong. The warm bulge collocated with the updraft core comes about through hydrostatic, dry, dynamic coupling, not through a latent heat process.

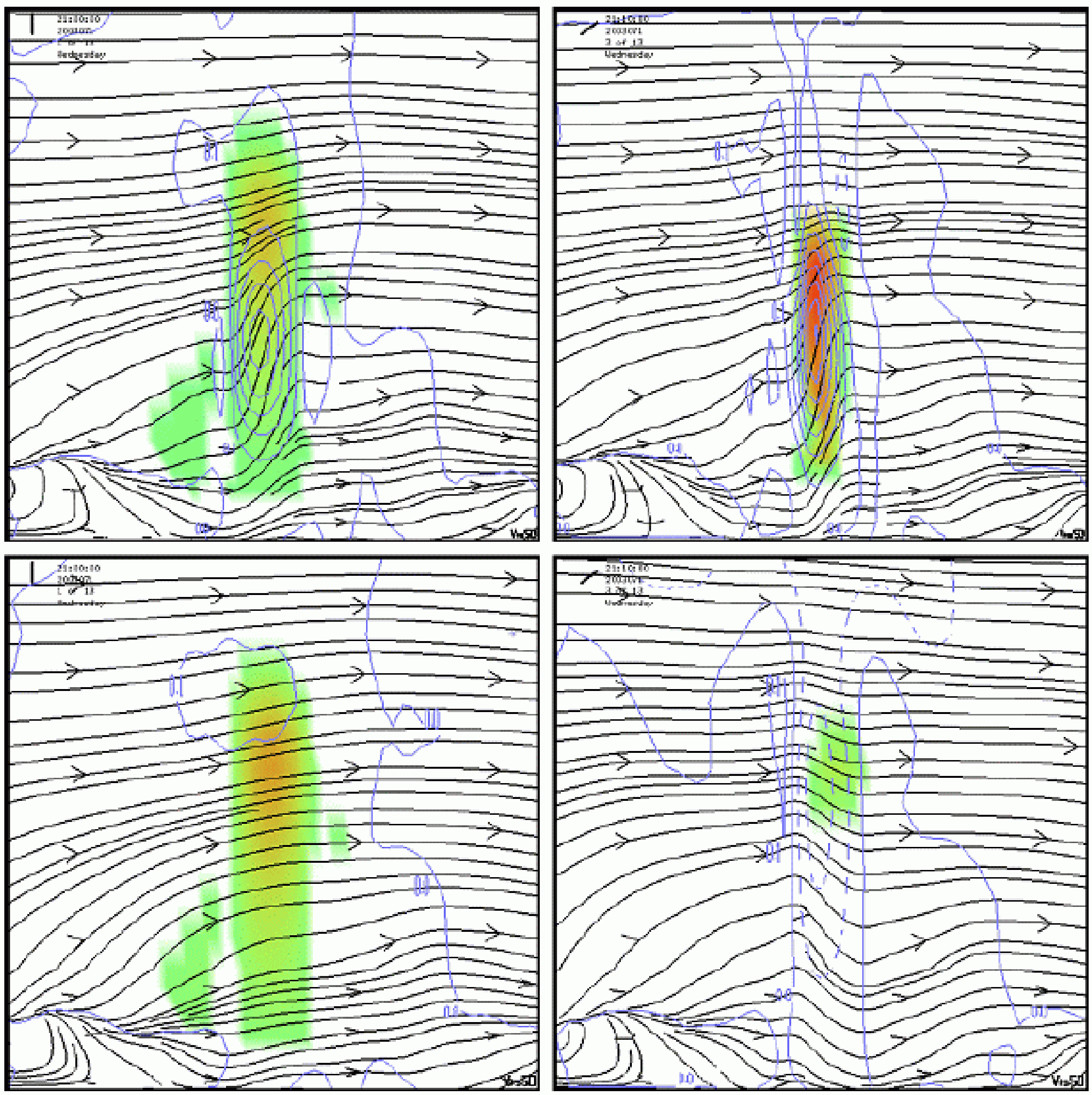


Fig. 3. Total condensate (shaded), vertical velocity (contours), and cross-section streamlines for analyses (right) and 5-min forecasts (left). The top pair shows LAPS hot-start DI with upward vertical motions where clouds are diagnosed and properly sustained cloud and vertical motions in the forecast; the bottom pair demonstrates the artificial downdraft that usually results from simply injecting cloud liquid into a model initialization without supporting updrafts or saturation.

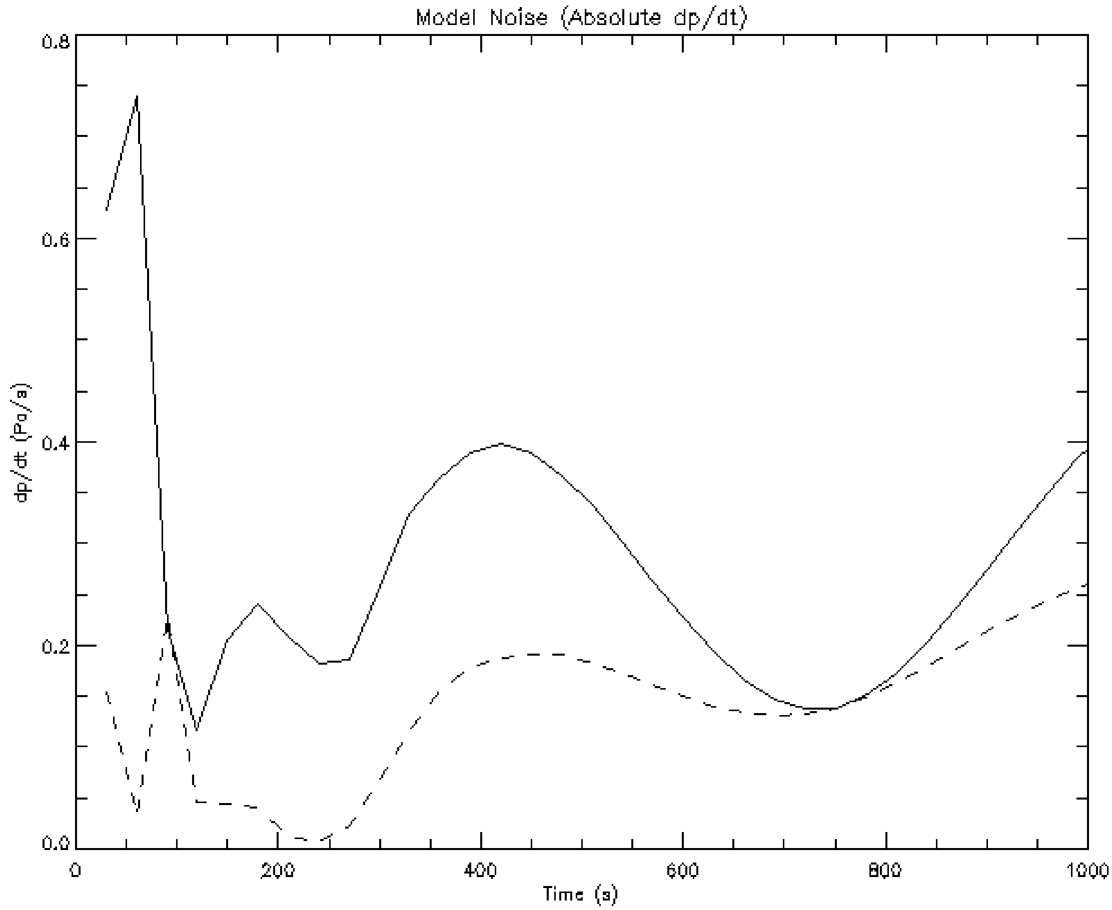


Fig. 4. Absolute average of surface pressure tendency over the grid for the first 200 seconds of a diabatically initialized MM5 run. This quantity is a good proxy for model noise caused by nonphysical gravity waves. The solution starting with the balanced initial condition (dashed line) evolves much more smoothly than the model run with unbalanced initial conditions (solid line).

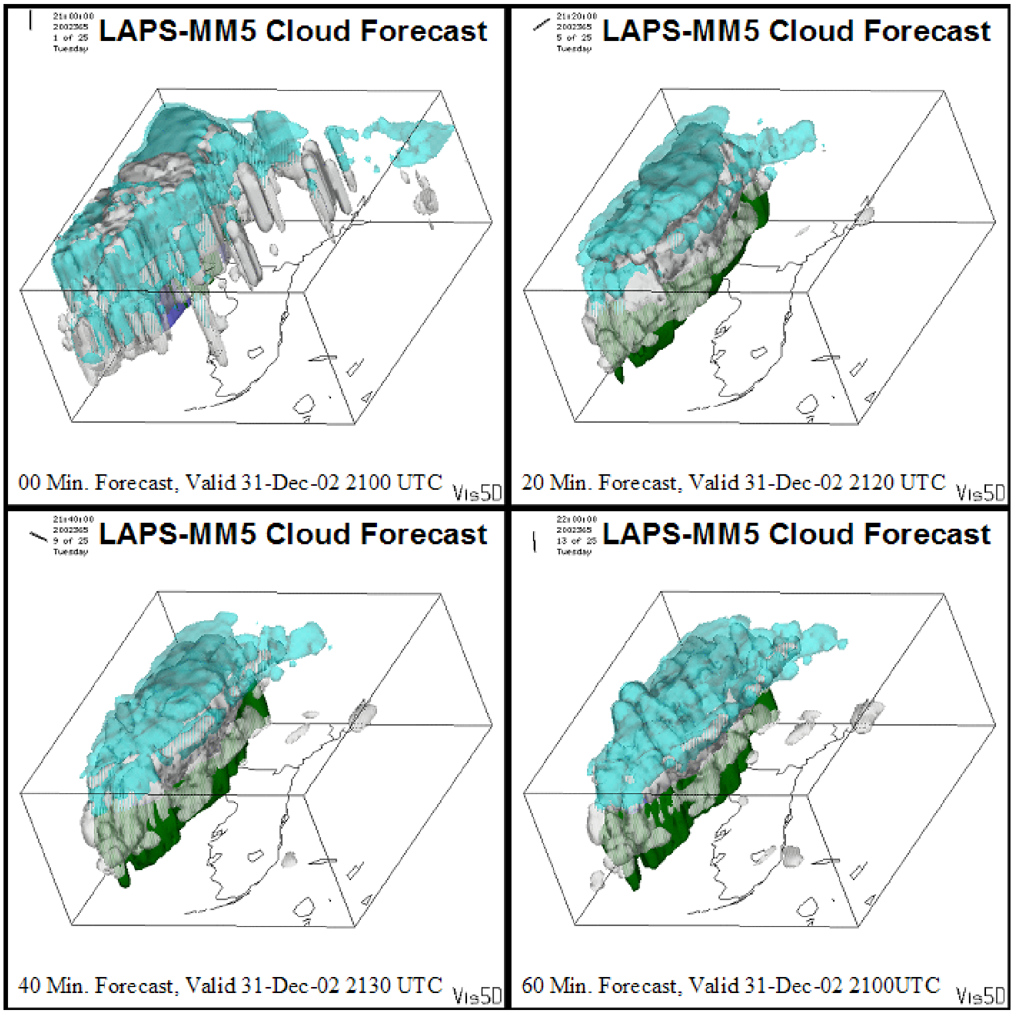
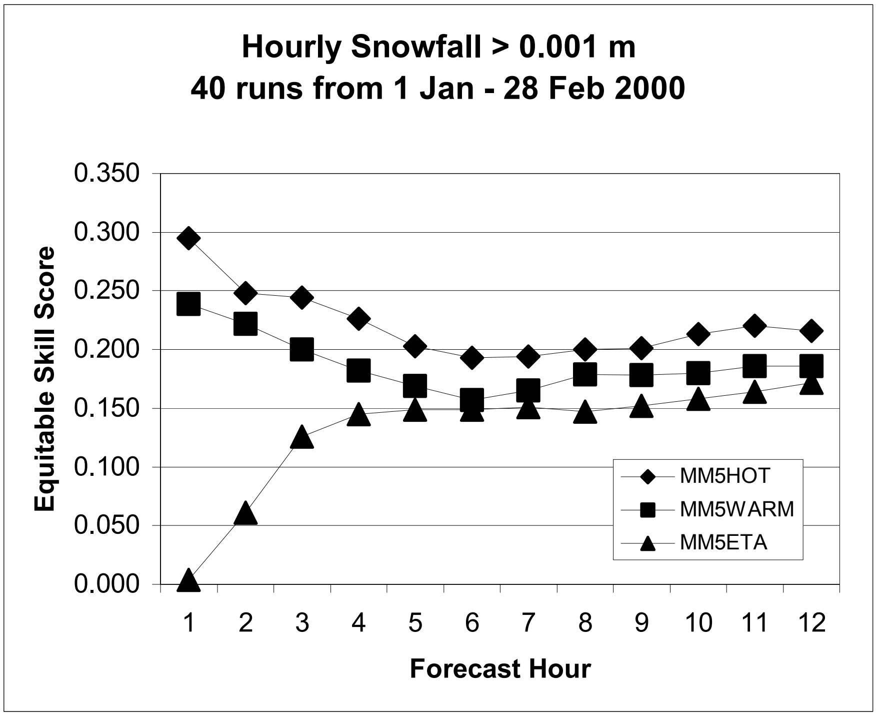


Fig. 5. Initial and forecast clouds at 20-min intervals from a LAPS diabatically initialized MM5 forecast. Hydrometeor species are color coded as follows: blue for ice, gray for cloud liquid, white for snow, and green for rain. In the first few minutes some of the smaller clouds vanish and some cloud liquid converts to cloud ice, but the main cloud system evolves realistically.

Fig. 6. MM5 forecast domains for three experiments. (a) 105x125 10-km Rocky Mountain domain; (b) 151x139 12-km IHOP domain; (c) 144x144 12-km MDSS domain**.**



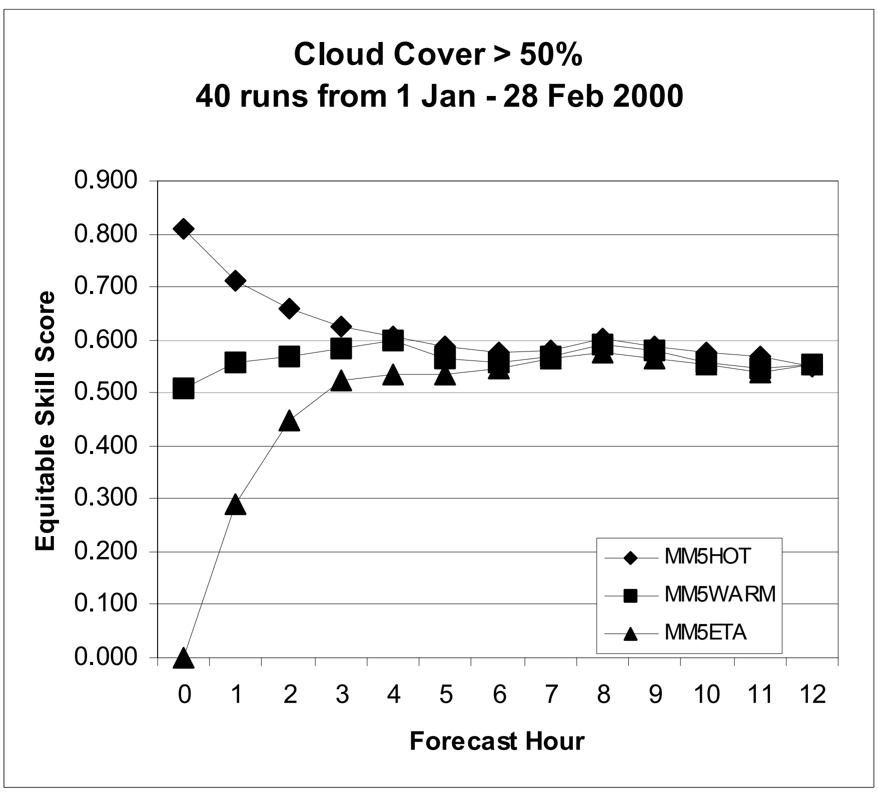


Fig. 7. Equitable skill score for hourly snowfall greater than 1 mm (top) and cloud cover greater than 50% (bottom) from the Rocky Mountain domain, October 2000-January 2001.

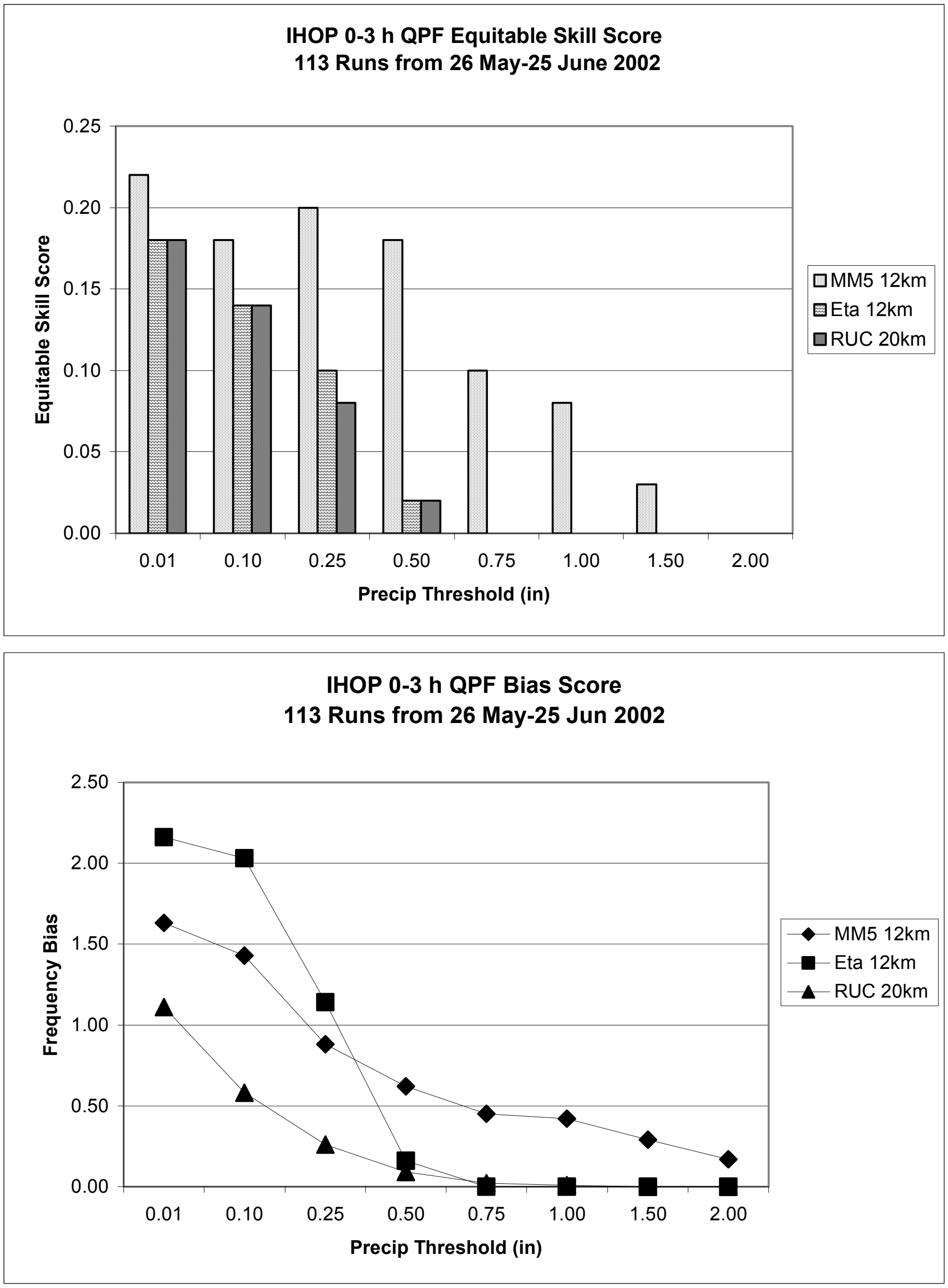
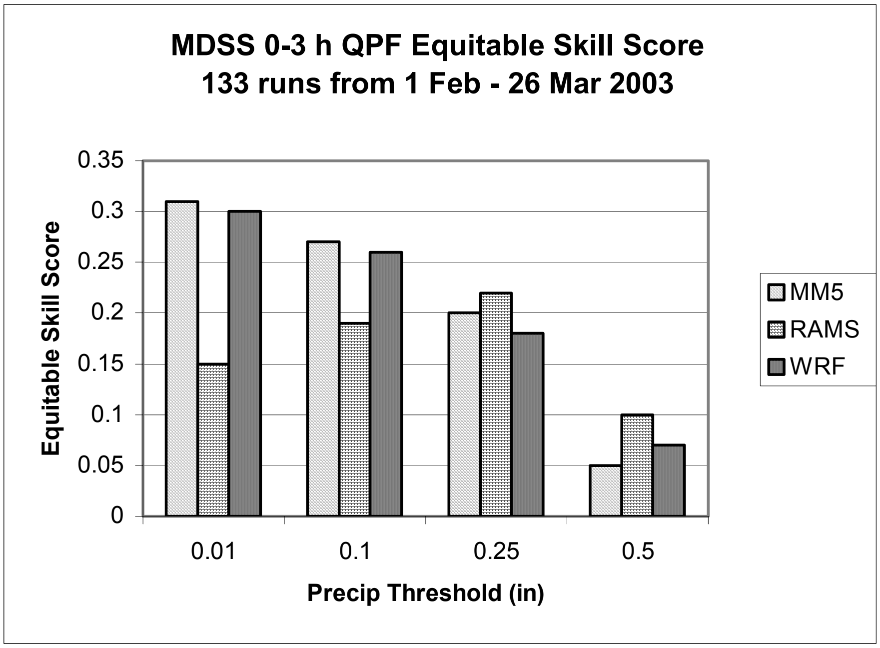


Fig. 8. ESS and Bias scores for 3-h QPF during the IHOP field experiment. The MM5 12-km was initialized with the LAPS DI method. The Eta 12-km is the NCEP operational Eta run, and the RUC 20-km was the developmental version run at FSL.



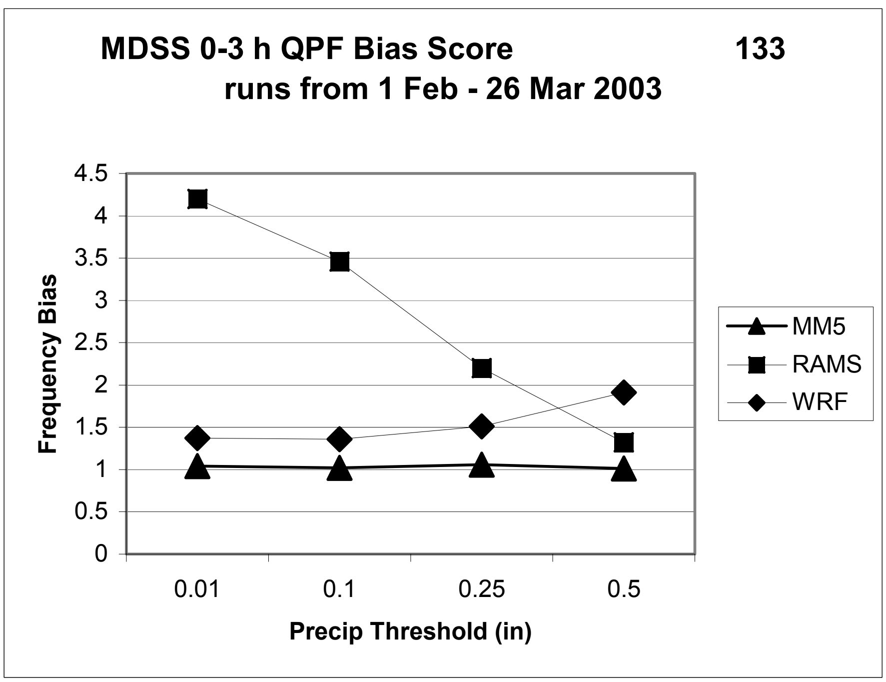


Fig. 9. ESS and bias plots for QPF during the MDSS experiment. Each of these model runs used the same grid configuration, hot-start initialization, and Eta lateral boundary conditions.